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Available range analysis of laser guidance system and its application to monolithic integration with optical tracker

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Abstract. A laser guidance alignment procedure for linear surgical tools by directly drawing two laser-beam lines onto the cylindrical tool surface was presented in our previous papers. In this paper, we describe feasibility analysis of the laser guidance alignment procedure. The available range of tool orientation and entry position is clarified in which accurate guidance is guaranteed. Further, a monolithic integration of the laser devices with an optical tracker is designed using the result of available range analysis. By monolithic integration, usability of the system is expected to greatly improve since the monolithic integrated laser devices can be intraoperatively relocated without the calibration. The details of parameter tuning in the monolithic design were reported. © 2004 CARS and Elsevier B.V. All rights reserved.

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1. Introduction

Laser-beam projection systems of surgical guidance information have recently been developed, in which laser-beams are directly projected onto the surgical field so that the surgeon can obtain the guidance information without looking away from surgical field to see the computer monitor [1–3]. In Refs. [1,2], a special procedure for alignment of linear

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surgical tools using the laser system was proposed, in which straight insertion path is displayed as an intersection of two laser planes generated from two laser devices. Since linear insertion is a quite common surgical procedure, the alignment procedure will have wide varieties of potential application domains. In the previous papers, alignment accuracy was validated [2] and the procedure was shown to be highly effective in various scenes of hip surgery [1]. However, the following problems remain. Firstly, available ranges in angle and position of linear tools to be aligned were not clarified. Secondly, calibration of the laser coordinate system with respect to the tracker coordinate system was needed every time the positions of the laser devices are changed relative to the tracker.

In this paper, we describe the following developments to solve the above problems. Firstly, we theoretically clarify the available range by answering the following questions: Given the positional arrangement of two laser devices, in what angular and positional ranges is the accuracy of linear tool alignment guaranteed? (Inversely, given the desired ranges, how should the laser devices be arranged?) Secondly, we rigidly attach the laser devices to the camera body of a optical tracker (Polaris, Northern Digital) to fixate the relation between the two coordinate systems. Here, the above available range analysis is effectively applied to determine optimal positioning of the laser devices relative to the camera so that the available range of the laser system is fit into that of the optical tracker. By monolithic integration of the laser guidance system with the optical tracker, usability of the system is expected to greatly improve since user calibration is unnecessary once the calibration has been done in the factory. Thus, the monolithic integrated system can be freely moved during the operation so that the laser beams are appropriately projected to the target as long as the reference marker of the tracker attached to the target is tracked.

2. Method

2.1. Guidance principle and necessity condition of accurate alignment

In the linear tool alignment procedure proposed in Refs. [1,2], the straight insertion line is defined as intersection of two laser planes in the physical space. As shown in Fig. 1, the projected two laser planes draw the entry point as crosshairs on the entry surface. When a cylindrical linear tool is aligned with the straight insertion line, the projected two laser planes draw two lines parallel to the cylinder axis on the cylindrical tool surface. If the linear tool is not exactly aligned, projected lines deviate from parallels. Due to high sensitivity of human visual perception on parallel lines, the surgeon can perceive slight

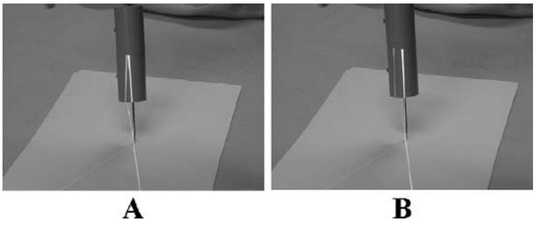

Fig. 1. Procedure of tool alignment justification. (A) Before orientation alignment; (B) after the tool has been aligned to the target orientation.

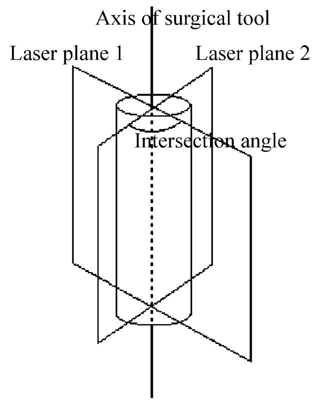

Fig. 2. Intersection angle.

deviation from parallels, and thus accurate alignment is possible by make the two lines parallel to the cylindrical axis.

In Ref. [2], it was experimentally shown that the accuracy of the linear alignment depended on the angle θ between the intersecting two laser planes (Fig. 2). The surgeons could align within 1° and 1-mm error when the intersection angle θ was between 30° and 100°. That is, 1° and 1-mm accuracy is guaranteed only when the angle θ is between 30° and 100°.

2.2. Available range analysis

Definition of available range: We define the available range of the alignment procedure as the range of angles and positions of the linear tools within which 1° and 1-mm accuracy is guaranteed. That is, the available range is defined as the range of the positions and angles of the tool axes given by the intersection of two laser planes whose intersecting angle θ is between 30° and 100°.

Representation and calculation of available range: As shown in Figs. 2 and 3, given the baseline length, L, of two laser devices, the intersection angle θ of the two laser planes can be obtained for any spatial line (which the tool axis is aligned to) through simple geometric calculation. Whether a spatial line of interest is within the available range is judged by

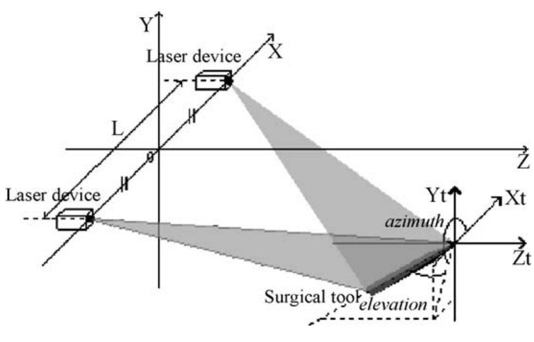

Fig. 3. Laser device and tool coordinate systems.

checking whether the intersection angle θ is between 30° and 100°. The available range is represented in the laser coordinate systems (LCS) whose origin and axes are defined based on the orientations and baseline of two laser devices. The "basic definition of the available range" is given by the available angular range of tool axis direction at each point (viewed as a tool entry point) of the LCS. Here, the angular range is represented as regions in the two-dimensional (2D) orientation space based on azimuth and elevation.

Definition of "available volume": Since the basic definition of the available range is somewhat difficult to directly combine with other conditions, we now define the "available volume" in the LCS as a set of (entry) points where the available angular ranges are sufficiently large, that is, more than 60° wide in both azimuth and elevation. The "available volume" are represented as regions in the physical space.

2.3. Integration with optical tracker

In reality, the shape of laser planes (beam tract) is sector whose center is the origin of the laser device. The sector angle was about 17° in our laser devices (which are controlled by galvanometer). We define the "projection volume" as the intersection volume where the both laser device can project and determined based on the baseline as well as the convergence angle α of the two devices. To integrate the two laser devices with an optical tracker in an effective way, the following conditions should be satisfied.

1. The "projection volume" is fit into the "available volume" of the laser guidance system.
2. The "projection volume" is fit into the "measurement volume" of an optical tracker.

3. Results

3.1. Accuracy validation of reposition planning simulational analysis of available angular range

According to the basic definition of the available range, the available angular ranges at various tool entry points were calculated. In the LCS, its origin was defined as the mid-point of the baseline of the two laser devices, its x-axis as the baseline, its z-axis as orthogonal to the baseline and passing through the center of the projection volume and its y-axis as orthogonal to other axes. The available angular range was represented in the polar coordinate system. The z-axis direction was the origin of the polar coordinate system, and the elevation (angle between the z-axis and the tool axis directions) and azimuth were represented as radius and angle of polar coordinates, respectively. The following characteristics of the available angular range were observed.

1. When the tool entry point moved away from the laser devices (that is, moves toward positive direction of the z-axis), the range became wider in elevation but narrower in azimuth.
2. When the tool entry point moved away from the z-axis along the x-axis, the range became narrower in azimuth while almost the same in elevation.
3. Between $z = 600$ mm and $z = 1020$ mm along the z-axis, the available angular range was more than 60° wide both in azimuth and elevation (that is, included in the "available

volume") when the baseline length, $L = 650$ mm (which was fit for the size of the Polaris camera).

3.2. Simulational analysis of available volume

The available volumes were calculated for the baseline length, $L = 600$, 650 and 700 mm. The available volumes became smaller in the z-direction for smaller baseline length while the same in the other two directions. The rectangle with 400 mm width (x-direction) and 400 mm depth (z-direction) could be fit into the available volume when $L = 650$ mm. The depths were, respectively, 380 and 470 mm when $L = 600$ and 700 mm, while the widths were the same irrespective of L. The center position of the available volume became nearer to the laser devices for smaller L. The recommended positions were $z = 900$, 950 and 1020 mm for $L = 600$, 650 and 700 mm, respectively. In summary, we finally obtained the following finding.

3.3. Validation of simulations

To validate the simulational available range analysis, the intersection angle θ of the actually projected laser planes was measured using Polaris pen-probe for various parameter settings. The error was defined as the difference between calculated and actually measured angles. The error was 0.13° in average and 0.54° in maximum, and thus the validity of the simulations were confirmed.

3.4. Design for integration of laser guidance system with optical tracker

Based on the above simulational analyses, monolithic integration of the laser devices with the Polaris camera was designed (Fig. 4). We assumed that the measurement volume

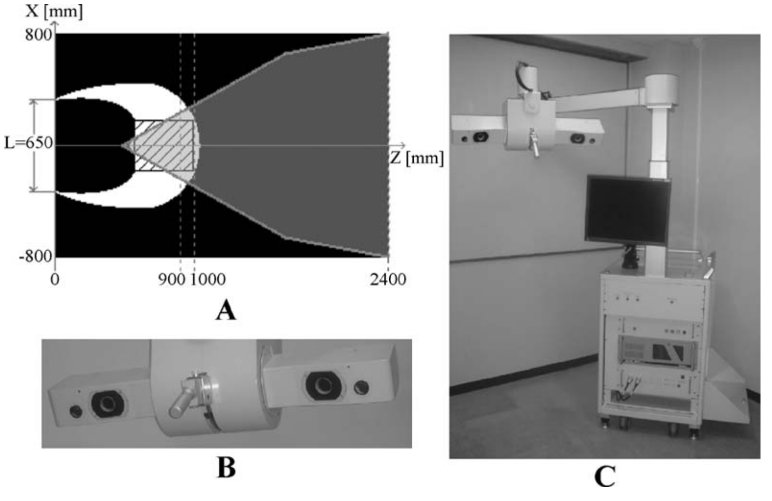

Fig. 4. Monolithic integration with an optical tracker, Polaris. (A) Available area map. The available area of the laser guidance system is shown as white. The measurement area of Polaris is shown as gray. (B) Monolithic integration of laser devices with Polaris camera. The base line length between two laser devices was 650 mm. (C) Appearance of whole system.

of Polaris was the pyramid volume (150% larger than the standard volume; see Ref. [4] for details). We aimed to apply to spine surgery. In the pyramid volume, the measurement area is around 400×400 mm^2 at $z = 1000$ mm, which is sufficient for spine surgery since the surgeon can freely move the monolithic system so as to project laser planes on the target area as long as the optical marker is fixated to the target vertebra. We confirmed that baseline length $L = 650$ mm and convergence angle $\alpha = 39.5°$ satisfied the conditions described in Section 3.3. Here, the recommended position and diameter of the projection volume was $z = 950$ mm and around 250 mm, respectively. The monolithic integration system with these parameters has already developed as shown in Fig. 4, and we confirmed that it actually worked.

4. Conclusion

We have described that simulational available range analysis of the alignment procedure for linear surgical tools using intersecting two laser planes. The simulations were validated by experiments using the actual laser guidance system. Based on the simulational analyses, the monolithic system integrating the laser system with Polaris camera was designed and developed. Due to the rigid connection of Polaris camera and the laser devices, user calibration has become unnecessary. The available range guarantees that the alignment accuracy is within one millimeter and one degree. However, it should be noted that slight deviation from the available range does not mean "perfectly unavailable". It means that accuracy will decrease and the system can alert in such cases.

Future work will include theoretical justification of the relation between alignment accuracy and the intersection angle between two laser planes. Currently, we are trying to quantitate the relations between the deviation from correct tool-axis orientation and that from parallels of the projected laser planes. In order to evaluate clinical usefulness, we are planning to apply the monolithic integration system to hip surgery as well as spine surgery. Further, the development of a commercially available product of the monolithic system is in progress by Hitachi, Japan.

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